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Study of Phase Distribution in Pipe Cyclonic Compact Separator using Wire Mesh Sensor

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ABSTRACT

Separation of gas-liquid mixture, which is achieved by using either large gravity separators or compact separators is a common and vital operation in the petroleum industry. Where space and cost are key project considerations, gas-liquid compact separators are very attractive because of their versatility and cost effectiveness. Efficiencient performance of the cyclonic separator depends on smooth and steady swirling flow. Unsteady swirling flow in the separator may be due to capacity constraint, improper design or unforeseen flow instability at the inlet. An understanding of phase distribution in gas discharge section of these separators would help design engineers make a better decision when selecting and sizing inlet nozzle, diameter and length of the separator. In this paper, the structure of phase distribution and liquid holdup in the gas discharge section of the separator was obtained using a 24x24 resolution wire mesh sensor (WMS). The acquired area average liquid holdup and the images were analysed using time series and 2D slice to discriminate between partial separation and critical separation condition.The liquid holdup as a function of separator inlet superficial velocity was quantified.

Keywords: Subsea separation, Swirling flow, cyclonic separator, liquid holdup, phase distribution, wire mesh sensor

Nomenclature

D	Dimensional
CFD	Computational fluids dynamics
ECT	Electrical capacitance tomography
cP	centipoise
ID	Internal diameter[m]
GLPC	Gas-liquid pipe cyclonic separator
PDF	Probability density function
t	time[s]
USL	Superficial liquid velocity[m/s]
USG	Superficial gas velocity[m/s]

1 INTRODUCTION

This paper presents recent research findings on application of WMS in monitoring phase distribution in the gas disengagement section of a gas-liquid pipe cyclonic separator. Cyclone separators are traditionally used for gas-solid separation in process plant for material recovery as well as pollution control. In the oil and gas industry, cyclonic separators are commonly used as hydrocyclone, mist eliminator, separator internals and compact metering system. The emergence of subsea separation is now driving interest in using cyclonic separator for bulk gas-liquid separation.The fundamental reason why cyclonic separators are attractive for subsea application is because of their small footprint in comparison to their gravity counterpart. Unfortunately, their small footprint brought about complex flow phenomenon particularly when the inlet flow condition is highly unstable or exceed the separator handling capacity.

The overarching effect of the complex flow phenomenon is what is termed liquid carryover. Liquid carryover is effectively the amount of liquid that is entrained in the gas stream as a consequence of partial phase separation. Eventually, the performance of the separator is defined based on the envelope for liquid carryover. This envelope is nothing but the combination of gas and liquid flow rate under which liquid carryover does not exist. It is therefore desirable that a cyclonic separator has a wide operating envelope for liquid carryover. It is suffice to say that at this moment in time, the oil and gas industry is yet to see this cyclonic separator with a wide operating envelope for liquid carryover.

Apparently, for subsea separation, various configurations of cyclonic separators are at various stages of concept study by various researchers and technology vendors. One thing that appears to be scarce is fundamental study about phase distribution and liquid holdup in the separator during liquid carryover. This understanding is important as it will help designers of this equipment to identify critical component of the separator that could be better engineered. Liquid hold quantification is important in developing empirical correlations or validating mechanistic models for pressure drop in the gas leg of the gas-liquid cyclone.

1.1. Description of the separation process

Figure 1 is a schematic diagram of a horizontal tangential inlet gas-liquid pipe cyclonic separator. The gas-liquid two-phase mixture in introduced tangentially into the separator body. As the flow enters the separator tangentially, centrifugal force acts on the phases causing them to swirl. The liquid phase because of its higher density is swung against the separator wall forming a liquid layer while the gas remained at the centre of the separator to constitute gas core. Buoyancy forces act on the gas phase causing it to rise upward. Gravity force prevailed on the liquid as it swirls downwardly. Under certain ranges of inlet flow rate of both phases; the gas phase will completely disengaged from the liquid and exit at the top as the liquid exit at the bottom of the separator. However, under adverse operating condition, the capacity of the separator is overwhelmed and the gas begins to strip the liquid upward and eventually carry it along to the gas exit. During liquid carryover, the flow in the separator gas outlet becomes typically gas-liquid two-phase flow. The liquid carryover could be droplets or large chunk depending on inlet flow condition and separator liquid level. The knowledge of phase distribution in the separator cross section is important when designing the separator and could be used for benchmarking the performance of various separation enhancement devices. For example, we know that the liquid always flows on the wall before being dragged into the exit pipe; we could design robust liquid film removal to improve separation performance. Similarly, knowing the amount liquid holdup during the carryover will help in validating pressure drop models. It is important to mention that phase distribution during liquid carryover is a very fast and highly dynamic process that is difficult to interpret by mere visual observation.

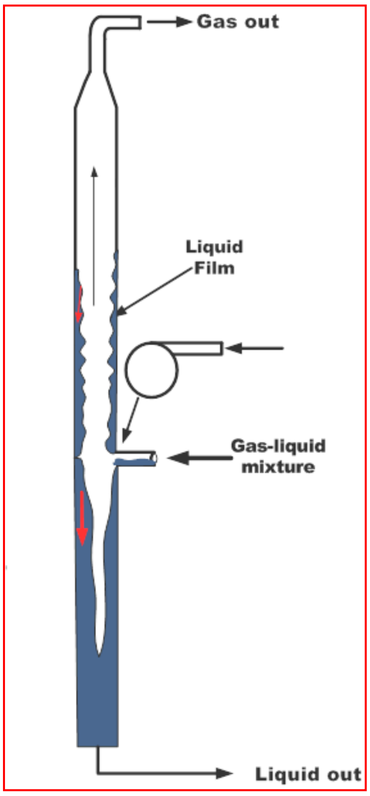


Figure 1 Schematic view of a Gas-Liquid Pipe Cyclonic Separator

Literature review show that there is little or no research with respect to measurement of liquid holdup and phase distribution at the gas outlet of a gas-liquid cyclonic separator during liquid carryover.Isaksen et al., [1], investigated the application of electrical capacitance tomography (ECT) to detect interphase level in a vessel type three phase separator. However, the use of ECT for this application has limitation because during liquid carryover, the droplet may not establish good contact with the electrode and this will affect the electrostatic field in the separator which may result to poor image resolution considering that ECT is non-intrusive device. Seriesrco density profiler are said to be very good for separator diagnostics [2], [3] but the authors are yet to stumble on literature showing the application of density profiler for liquid holdup measurement in cyclonic separator. Considering that liquid carryover phenomenon is very dynamic, one could rather rely on average holdup up to estimate mixture density rather using radioactive seriesrs; moreover, radioactive substance poses a health risk. Erdal et al.[4] applied CFD in estimating void fraction distribution in GLCC. However, this model was not validated due to lack of experimental data. Kataoka et al.,[5] and; Jaworski and Meng,[6] used high speed video camera to visualise and then manipulated the image using C++ code to estimate the void fraction. If the separator is not made of very clear acrylic pipe, this approach cannot be applied and for dynamic phenomenon like liquid carryover the result of this manipulation may suffer from high level of uncertainty. Wire mesh sensor is widely used for measurement of void fraction in multiphase flow pipes. Shaban and Tavoularis [7] used wire mesh sensor for measurement of gas and liquid flow rate in a gas-liquid two-phase flow pipe. Olerni et al., [8] applied wire mesh sensor to measure air distribution and void fraction in vertical upward air–water flow. Da Silva et al.,[9] compared accuracy of wire mesh sensor to that gamma densitometer and good agreement between two measurement instruments was reported.

2 Experimental Setup

2.1 Description of the experimental facility

The experiment was conducted in a 3” (76.2 mm ID) and 2.7 m tall gas-liquid pipe cyclone (GLPC) separator test facility at Cranfield University, UK. As shown in Figure 2, the test facility is a closed loop system consisting of fluids supply and metering section, GLPC separator and fluids return section. Air and water were used as test fluids and referred to as gas and liquid respectively in other parts of this paper. Liquid and gas from the fluid supply via a metering section enter the mixing point to form two-phase mixture. From the fluids mixing point, the two-phase mixture enters the GLPC separator through a 1.5” (38 mm ID) horizontal inlet where the mixture is separated into liquid and gas. The length of the horizontal pipe from the mixing point to the tangential inlet of the separator is 3.6 m. Finally, the separated liquid returned to the storage tank while the gas is vented out.

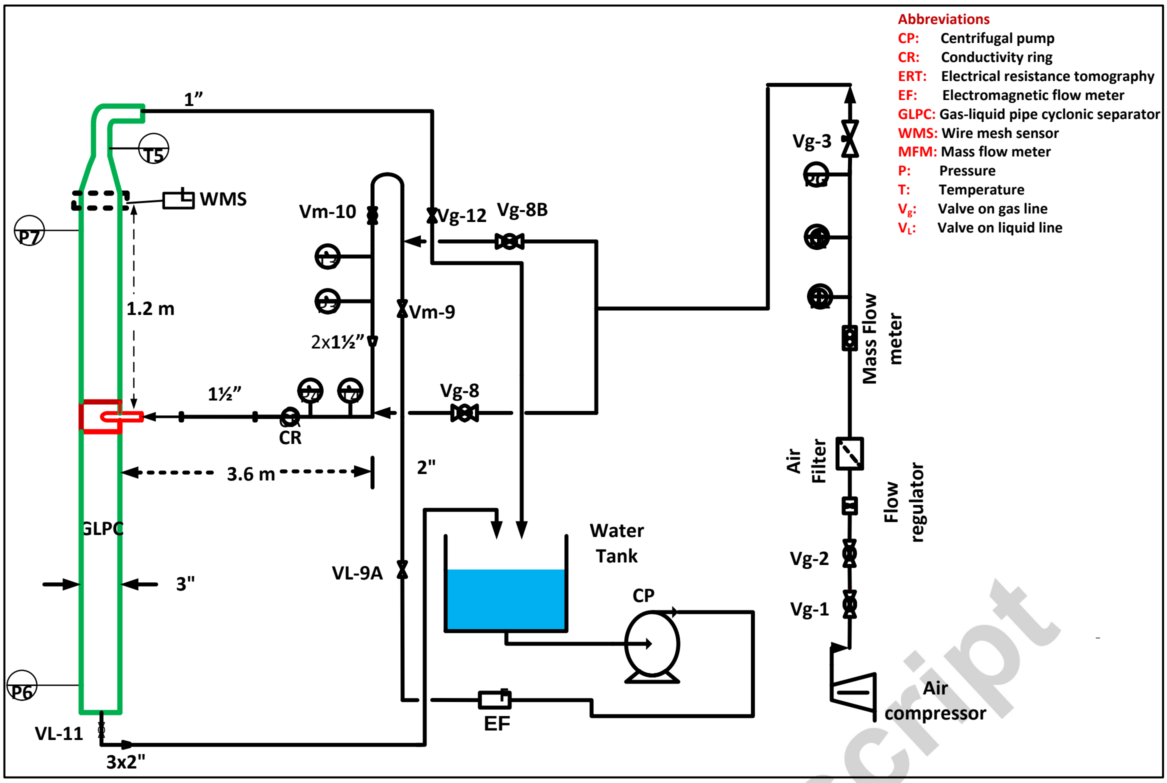
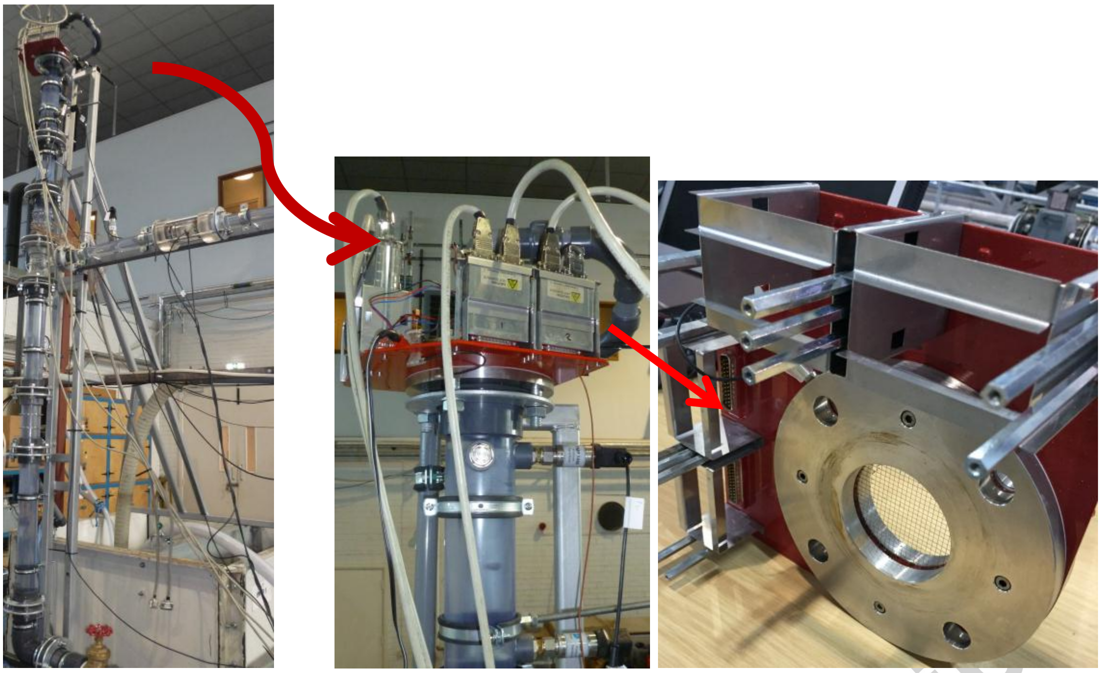


Figure 2: Experimental Setup

The required air was metered using Endress+Hauser thermal mass flow meter (Proline t-mass 65) before entering the flow loop. Water is supplied to the flow loop by Certikin Aquaspeed self-priming pump which has a maximum duty of 4 l/s at 3 barg. It is metered using ABB electromagnetic flow meter.
The test area consists mainly of the GLPC separator (with associated instrumentation) where separation of gas from the liquid takes place. The gas outlet pipe is 1” while the liquid outlet is 2” pipe. A gate valve is installed on the gas and liquid outlet for manual control of separator pressure and liquid level respectively.

2.2 Wire mesh sensor

In this research, capacitance wire mesh sensor was used for liquid holdup measurement and flow visualisation during liquid carryover in GLPC separator (Figure 3a). The capacitance wire-mesh sensor (see Figure 3b) was developed by Helmholtz-Zentrum Dresden-Rossendorf (HZDR) for the measurement and visualisation of multiphase flow of both conducting and non-conducting fluids. It is an invasive flow measurement technique with high spatial and temporal resolution. The wire mesh sensor used in this work is capacitance type. The measurement principle is based on the relative permittivity of the material present in the flow [9].The permittivity distribution over the cross sectional area of separator is a function of the amount of material present. The capacitance wire mesh sensor used in this work in 76.2 mmID and consists of two planes of wire electrodes known as receiver and transmitter. Each plane has 24 stainless steel wires of 0.12 mm diameter, with inter-wire gap of 3.175 mm within each plane and 1.5 mm axial plane distance. The wires of each plane runs parallel to each other but perpendicular to the wires of the other plane thereby forming a mesh with equal spacing except towards the pipe wall. The wires are mounted on a stainless steel flange making the sensor very robust and easier to install in the cyclonic pipe separator. The WMS was installed in the separator at a height of 1.2 m from the separator inlet centreline.The technical detail behind calculation of liquid holdup using WMS is well presented in the paper by Prasser et al., [10] as well as in the WMS data processing manual [11].



(a) (b)

Figure 3(a) Gas-liquid pipe cyclonic separator with installed wire mesh sensor (b) Wire mesh sensor

2.3 Experimental test matrix

In order to take measurements using wire mesh sensor, calibration file for both high and low permittivity material were first made using the procedure in [11]. The experiment was conducted using the test matrix presented in Table 1. This test matrix was carefully selected so that critical separation (prior to liquid carryover) and partial separation (liquid carryover) would be achieved. The flow regime at the inlet of the separator for this test points was dispersed annular flow. This flow regime was characterised by liquid film at the bottom of the pipe and aerated flow occupying the top. This flow regime was not responsible for liquid carryover (LCO) in the separator. The liquid LCO under this test matrix was attributed to capacity constraint of the separator.

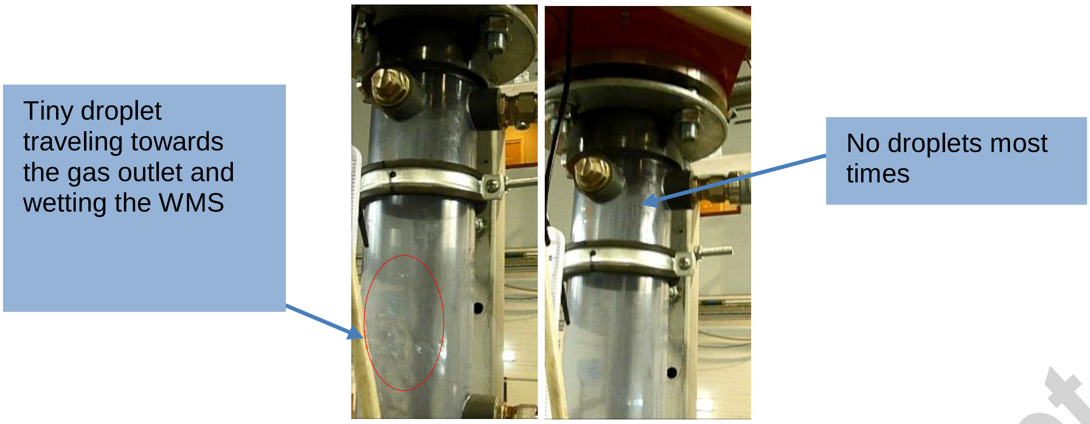
Table 1 Experimental test matrix

Test	U_{SG} (m/s)	U_{SL} (m/s)	Viscosity (cP)
1	12.18	1.45	1.0
2	12.64	1.45	1.0
3	8.79	2.14	1.0
4	5.70	2.14	1.0
5	10.02	1.80	1.0
6	10.74	1.80	1.0
7	7.89	2.52	1.0
8	7.52	2.52	1.0
9	5.27	3.15	1.0
10	4.43	3.15	1.0

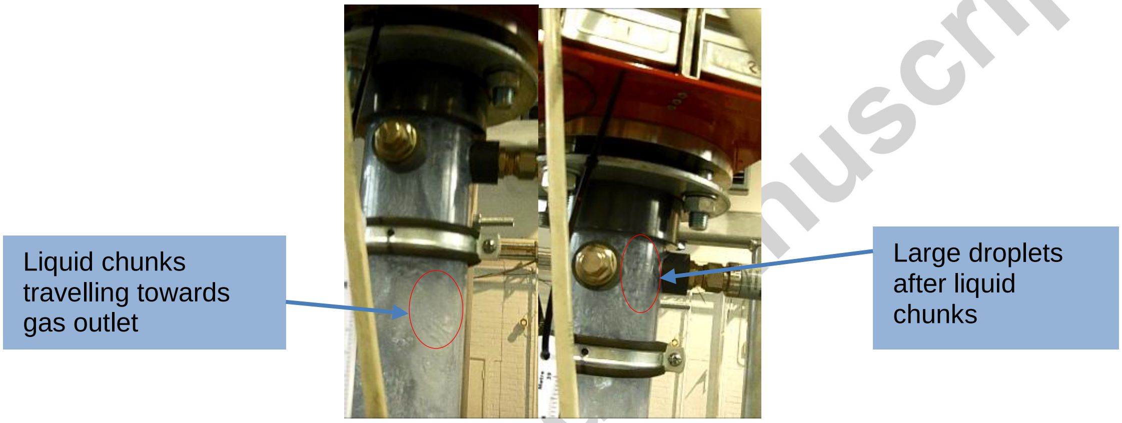
3 Results and discussion

3.1 Image of phase distribution

The images of phase distribution in the section of interest provides us with good information of what is happening inside the separator and this can be use to optimise the design of the separator. The images presented in this work are for two operating conditions of the GLPC separator namely: critical separation and partial separation. The critical separation corresponds to maximum separator inlet gas and liquid flow rate for maximum separation efficiency. Any slightest increase in either gas or liquid flow rate above this maximum condition could results to partial separation.The partial separation operating condition corresponds to liquid carryover to the gas outlet. During the critical operating condition, tiny liquid droplets were iniatially entrained in the gas stream but eventually deposited on the separator wall near the gas outlet. Some of the droplets collides with the wires and consequently wetted the wires. Snapshot of the image taken during critical separation and partial separation is presented in Figure 4.



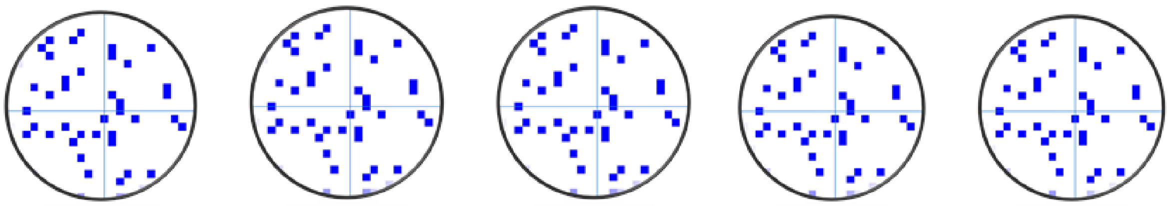
(a) Critical separation



(b) Partial separation (liquid carryover)

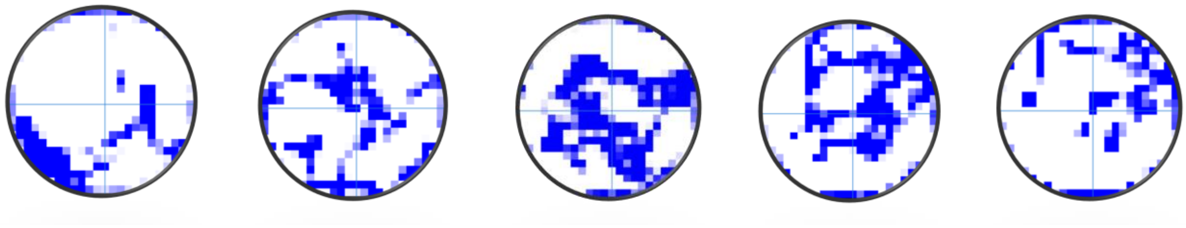
Figure 4: Snapshot showing phase distribution in the gas disengagement of the separator

Figure 5a and 5b represents the 2D images of the phase distribution in the separator cross sectional in x-y plane obtained from WMS framework. Each of the 2D images represent a single frame at a time interval of 10 ms. Blue and white colour represent water and air respectively as shown on the colour scale. Figure 5a represent the images of the phase distribution when the separator was operating in a critical separation condition prior to liquid carryover. The superficial velocity of gas and liquid for this condition were U_{SG} =7.52 m/s and U_{SL} = 2.52 m/s respectively. The white space implies that air was the dominant material flowing at that time in the cross section of the separator and vice vasa for liquid. It can be seen that throughout the sampling period from t_1 to t_6 there is no variation in the images. The implication is that the separator is not operating in liquid carryoover regime. Though, there are blue spots but this spots are just an indication that the wires are getting wet due to the fact that the separated air is not fully dried.



t_1=10 ms t_2=20 ms t_3=30 ms t_4=40 ms t_5=50 ms

(a) Gas superficial velocity U_{SG} = 6.72 m/s and liquid superficial velocity, U_{SL} = 2.52 m/s



t_1=10 ms t_2=20 ms t_3=30 ms t_4=40 ms t_5=50 ms

(b) gas superficial velocity U_{SG} =7.52 m/s and liquid superficial velocity, U_{SL} = 2.52 m/s

Gas fraction (Colour scale)

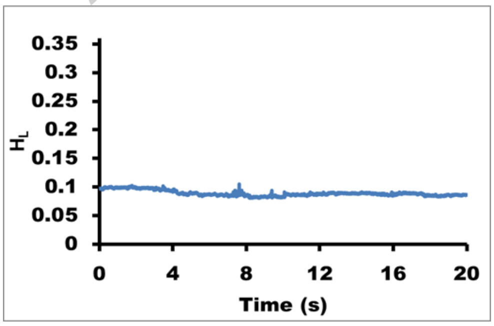
0% 100%

Figure 5: 2D image (top view) of phase distribution in the gas outlet of the separator during liquid carryover

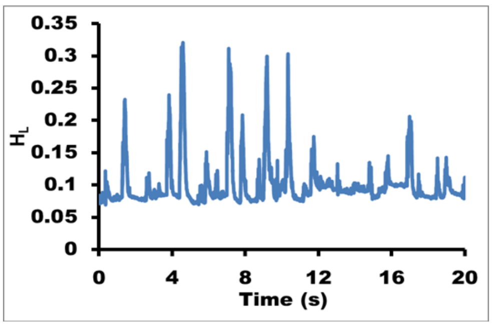
Figure 5b represents the images of the phase distribution when the separator was operating in the partial separation regime. While the liquid flow rate was kept constant at 2.52 m/s, the superficial velocity of the gas into the seperator was increased from 6.72 m/s to 7.52 m/s. This increase resulted to partial separation as a as the liquid was seen in the gas outlet liquid carryover. From t_1 to t_6 in Figure 5b, the phase distibution changes with time in an irregular manner.The structure of the phase distrisbution is driven by gas flow in the inlet of the separator. When the inlet gas velocity exceeds the design capacity of the separator, the separated liquid film on the wall of the separator becomes very wavy and the rate of entainment into the gas core far exceeds the rate of film drainage into the liquid disengagement section of the separator.

3.2 Comparison of pressure transducer and WMS using time series

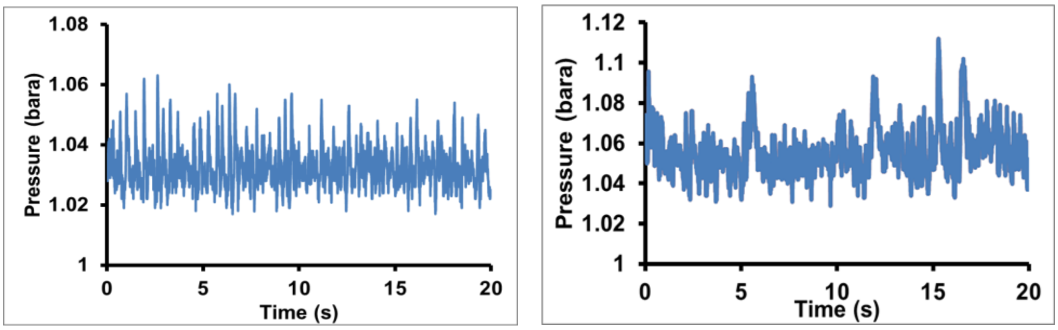
Useful information about the phase distribution in the gas disengagement section of the GLPC separator could be obtained from WMS by analysing the time varying cross sectional liquid holdup. Though measurement of instantaneous wall pressure was not part of this research, but to increase confidence in the results obtained from WMS sensor, wall pressure time series data were obtained and compared with liquid holdup time series. The comparison was made on the basis of critical separation and partial separation. As shown in Figure 6a and c, both the liquid holdup and wall pressure fluctuation time series for this condition are reasonably steady. This is because the amount liquid entrained in the gas stream was not sufficient to cause flow fluctuation and changes in permittivity of the medium in the separator cross section during the sampling period. It was observed during the experiment that liquid droplets were jumping towards the WMS quite often but the velocity of the rising gas stream was not sufficient to pull the liquid droplets along to the outlet. Increasing the inlet superficial gas U_{SG}=8.99 m/s to U_{SG}=10.70 m/s at a constant U_{SL}= 1.80 m/s resulted to partial separation of liquid and gas. The partial separation condition presented in this work was characterised by intermittent flow as can be seeing by the significant variation of liquid holdup time series and wall pressure fluctuation in Figure 6b and d. The variation coincided with the observed pulsation of liquid towards the outlet. Fundamentally, it is true to say that the flow domain is a reflection of the amount of either the low or high permittivity present. It is important to mention that liquid carryover is very sensitive to increase in either liquid or gas flow rate.



(a) U_{SG} = 8.99 m/s



(b) U_{SG} = 10.70 m/s



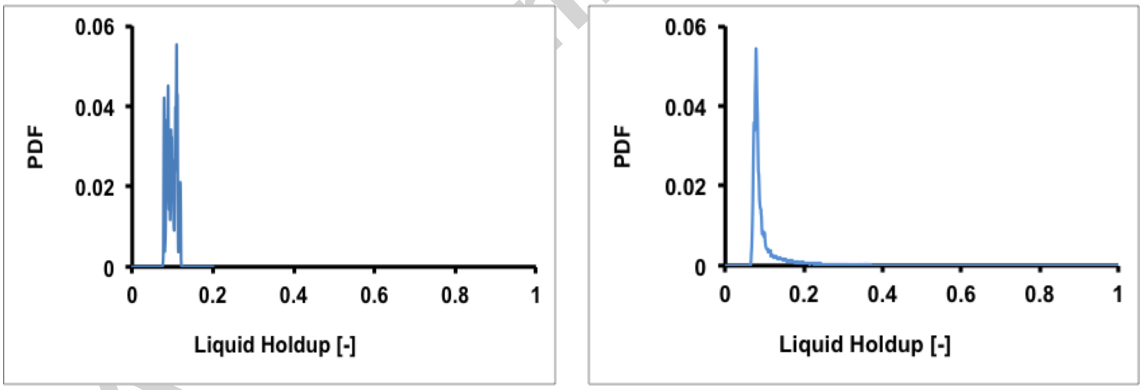
(c) U_{SG} = 8.99 m/s

(d) U_{SG} = 10.70 m/s

Figure 6: Comparison of time series of Pressure Transducer and WMS at constant inlet U_{SL} = 1.80 m/s for: (a) and (c) critical separation while (b) and (d) partial separation

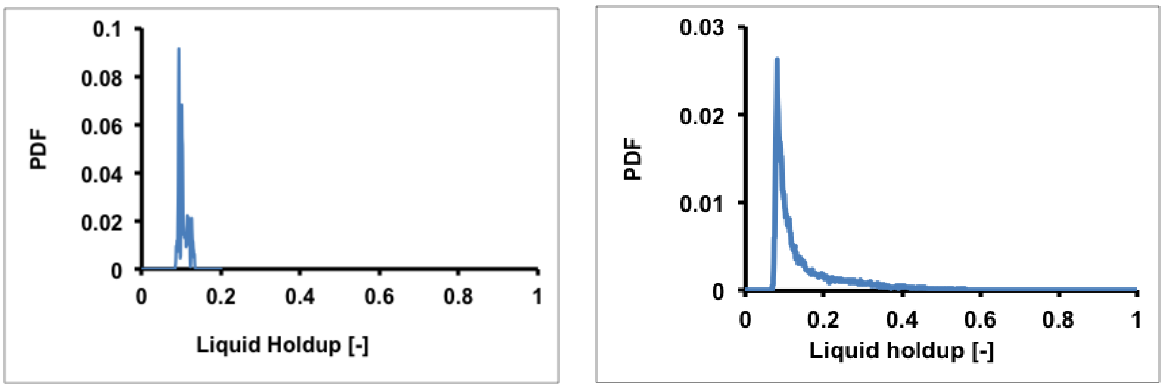
3.3 Probability density function of time variant liquid holdup

When only gas leaves the gas outlet of the separator due to complete separation, the magnitude of turbulent fluctuation is expected to be less compare to when the gas is carrying liquid droplets. Therefore steady flow is achieved rather than intermittent flow. The average cross sectional liquid holdup from WMS was used to obtain the probability density function (PDF) of the time varying cross sectional liquid holdup. Probability density function (PDF) is widely used for flow pattern identification using wall pressure data as well as void fraction [12]–[14]. In Figure 7a and 8c, it can be seen that the probability density function (PDF) of the cross sectional liquid holdup for different inlet liquid and gas superficial velocity is very consistent. As long as the gas and liquid flow rate is within the threshold of critical separation, the amount of liquid droplets in this section of the separator appears to be relatively uniform. In the case of partial separation where the flow behaviour in this section of the separator is chaotic and oscillatory, the phase distribution is not uniform as exhibited with the wider base of the time series and PDF in Figure 7b and 8d. The flow behaviour during the partial separation exhibit similar characteristics as churn flow.



(a) U_{SG}=7.89 m/s; U_{SL}= 2.14 m/s

(b) U_{SG}=8.79 m/s; U_{SL}= 2.14 m/s



(c) U_{SG}=6.72 m/s; U_{SL}=2.52 m/s (d) U_{SG}=7.52 m/s; U_{SL}=2.52 m/s

Figure 7: Liquid holdup time series and probability density function for ('a' and c') critical separation and ('b' and 'd') partial separation.

3.4 Area average liquid holdup

Liquid holdup measurement is generally important for calculation of pressure drop, separator operating envelope and the steady state liquid content in the gas flowline [15]. Liquid build-up in gas flowline as a result to liquid carryover in Caisson subsea separator was identified by Atakan et al., [2] as critical parameter that reduced the hydraulic efficiency of gas flowline. Previous research effort at Tulsa by Chirinos et al.,[16] to measure and estimate the percentage liquid carryover was to install a 6 inch liquid trap pipe in the outlet of the GLCC separator so as to trap the liquid leaving the separator in form of carryover. Rosa et al.,[17] installed a demester at the outlet of their Cyclonic Separator (CS) to capture and measure liquid carryover. While these approaches are simple and straightforward, they cannot be applied to critical separation scenario whereby liquid droplets travel up to the top of the separator near the gas exit pipe but ends up depositing on the separator wall. This approach is also prone to errors considering the intermittent nature of the liquid carryover as well as inefficiency of the liquid trap pipe or demester flooding.

In Table **2**, maximum, minimum, average and standard deviation for liquid holdup for various inlet gas and liquid superficial velocities have been presented. It can be seen that the liquid holdup is a function of both liquid and gas superficial velocity. However, for a constant liquid superficial velocity, the liquid holdup tends to increase with increasing gas superficial velocity. For example, increasing U_{SG}=12.18 m/s to 12.64 m/s at constant U_{SL}=1.45 m/s resulted to increase in liquid holdup from = 0.11 to 0.12.This is because as the gas flow rate is increased; more liquid droplets are being formed due to increase in liquid entrainment rate. Also, the droplets coalesced and formed even larger liquid chunks resulting to increase in the relative permittivity cross the measurement domain. This larger droplet tries to fall downward due to force of gravity but rather falls against the fast rising gas. Consequently, the droplets are transported out of the separator with the gas. These droplets can become even worst if the liquid level in the separator is not kept below the inlet. Using WMS, we are able to quantify the liquid holdup for the critical separation operating condition.
Analysis of the maximum, minimum, average and standard deviation we came to a conclusion that good separation can only be achieve in the GLPC separator only when the liquid holdup near the gas exit is $H_L \leq 0.10$.This value is within the maximum and minimum liquid holdup for all cases of the critical separation investigated.

Table 2: Quantitative features of cross sectional liquid holdup for critical and partial separation

U_{SG} (m/s)	U_{SL} (m/s)	U_m (m/s)	Max Holdup	Min Holdup	Average Holdup	Standard Deviation	Comment
12.18	1.45	13.64	0.15	0.09	0.112	0.014	Critical separation
10.02	1.80	11.82	0.14	0.08	0.089	0.005	Critical separation
7.89	2.14	10.03	0.13	0.08	0.098	0.012	Critical separation
5.70	2.52	8.22	0.11	0.09	0.103	0.003	Critical separation
4.43	3.15	7.58	0.20	0.10	0.111	0.005	Critical separation
12.64	1.45	14.09	0.15	0.10	0.123	0.008	Liquid carryover as liquid droplets
10.74	1.80	12.54	0.43	0.06	0.100	0.039	Liquid carryover churn flow
8.79	2.14	10.93	0.61	0.06	0.098	0.047	Liquid carryover as liquid droplets
7.52	2.52	10.05	0.71	0.07	0.151	0.100	Liquid carryover as churn flow
5.27	3.15	8.40	0.73	0.07	0.245	0.147	Liquid carryover as churn flow

4 Conclusion

Wire mesh sensor method provides good information about the structure of phase distribution in the separator outlet as well provide quantitative information about the area average liquid fraction for both critical separation and partial separation operating mode. When the separator was not experiencing liquid carryover, liquid holdup time series and 2D images showed no variation with respect to time. However, during liquid carryover phenomenon, there were significant variations in liquid holdup due to the intermittent nature of the liquid flow in the gas outlet. The area average liquid holdup as a function of separator inlet superficial gas velocity was also quantified. The authors believed that liquid holdup measurement during liquid carryover phenomena can help in better prediction of separator pressure drop and steady state liquid holdup in separator gas flowline.

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Highlights

- Wire mesh sensor provided useful information about phase distribution in the gas discharge section of gas-liquid pipe cyclonic separator
- During partial separation which was characterised by liquid carryover inform of heavy mist and churn flow, there were significant variations in liquid holdup
- The average liquid holdup near the gas exit must be less than 0.10 for complete separation to be achieved

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Study of phase distribution in pipe cyclonic compact separator using wire mesh sensor

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